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(54) Improvements relating to positional information systems

(57) A positional information system has a transmitter with a set of coils (1,2,3) having three mutually orthogonal axes (X,Y,Z). These are energised in pairs with a.c. in a phase relationship that, for each pair, generates a resultant field (A,B,C) rotative about the axis of the other coil. In the form shown, a receiver has a coil and the phase relationship of the signal induced in it to the transmitted signals gives a positional relationship. More information is available from three mutually orthogonal receiver coils (Figs. 3,5 not shown). The receiver may be attached to a soil-piercing tool or mole.

In another form, the internal magnetic field of the transmitter coils is used in a tilt meter or directional accelerometer. A magnetically susceptible body (20, Figs. 7–9 not shown) suspended within the transmitter coils (1,2,3) induces secondary signals in the coils whose phase relationship indicates the orientation of the body (20).

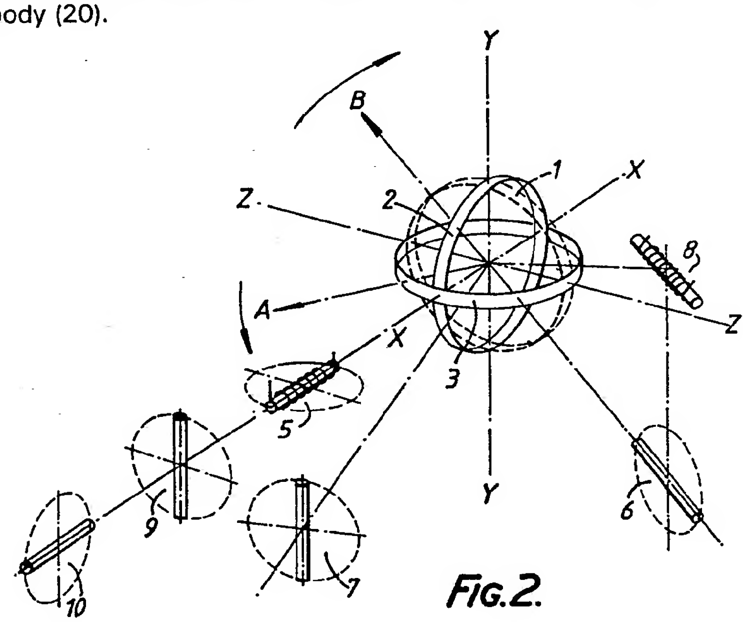

FIG.2.

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The drawing(s) originally filed was/were informal and the print here reproduced is taken from a later filed formal copy.

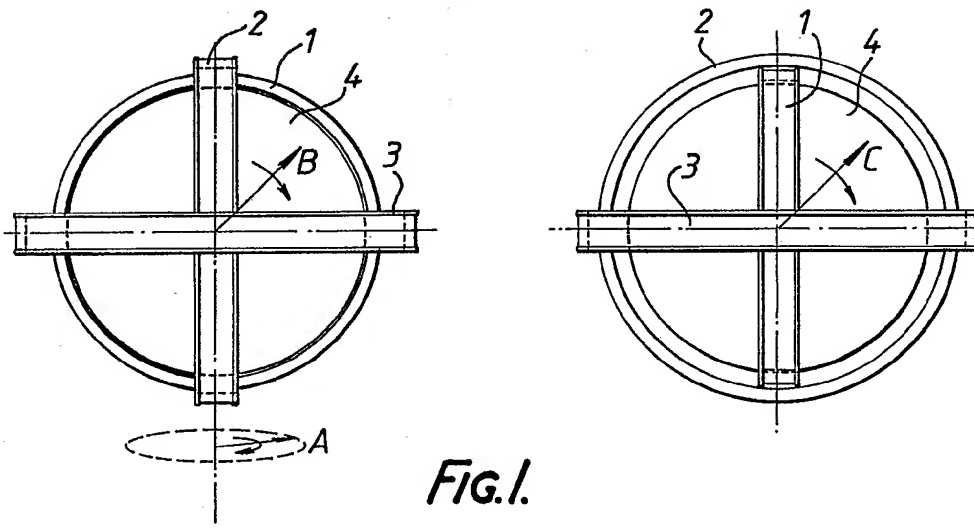

FIG.1.

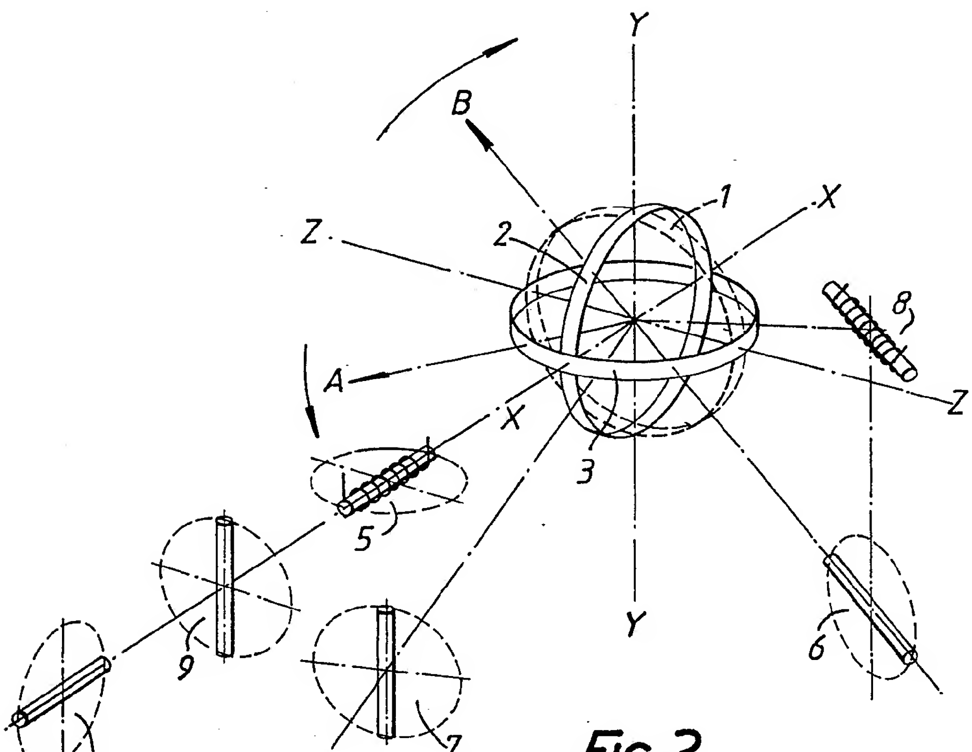

FIG.2.

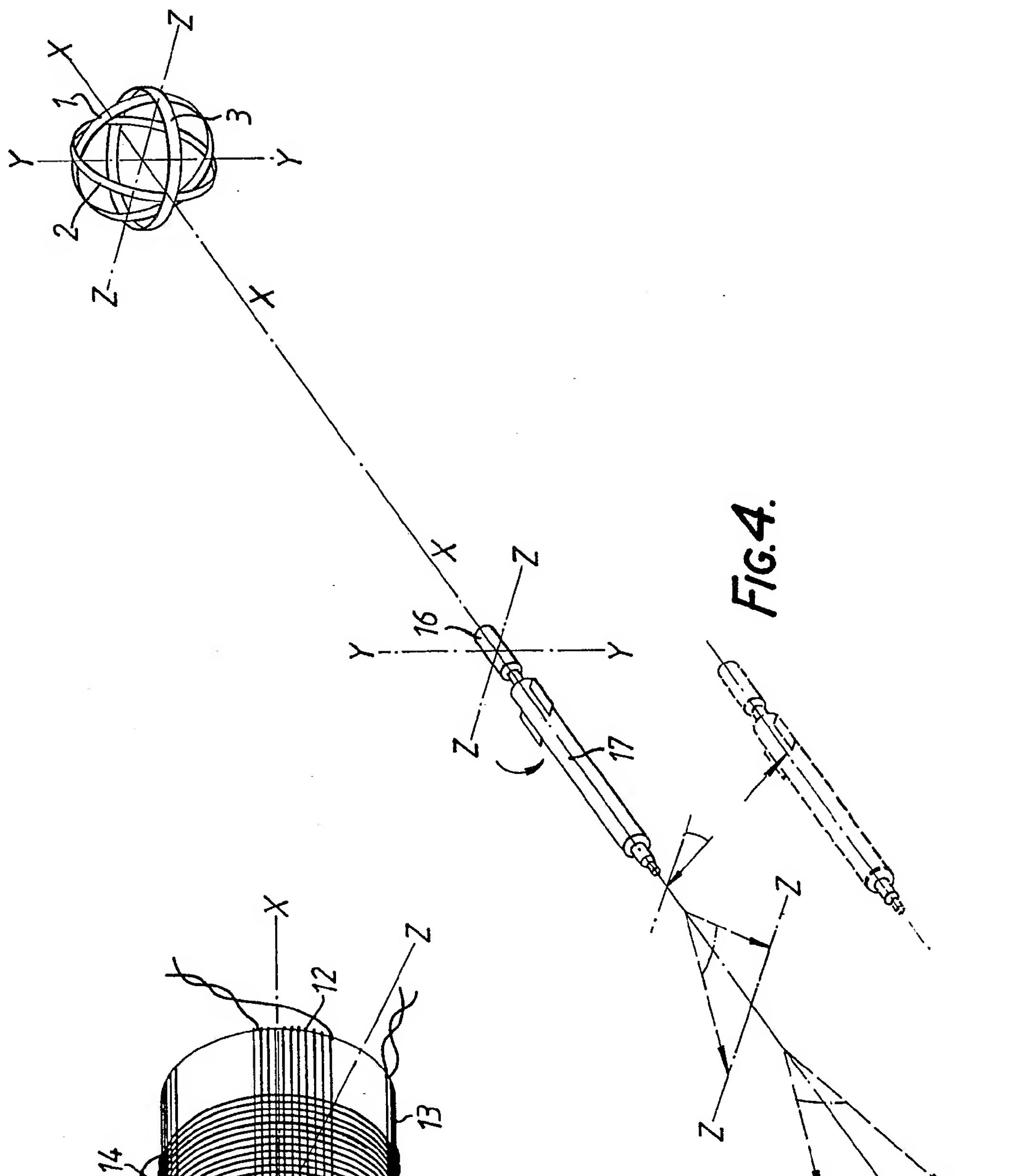

FIG.4.

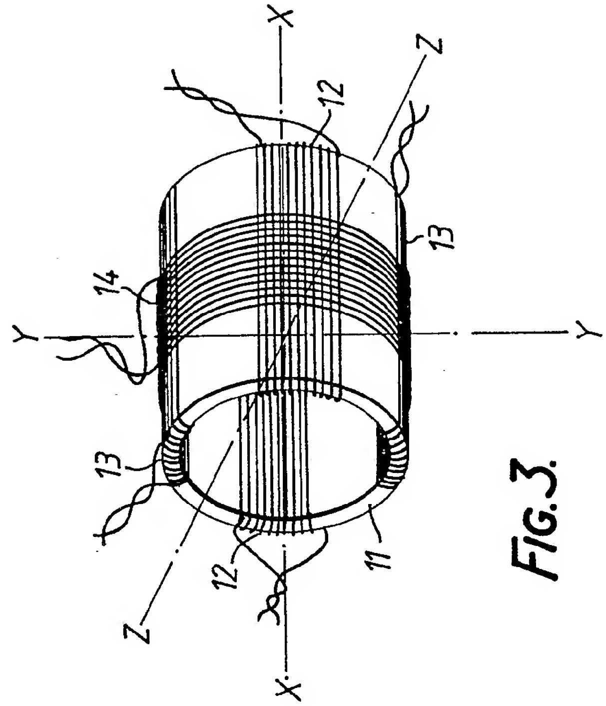

FIG.3.

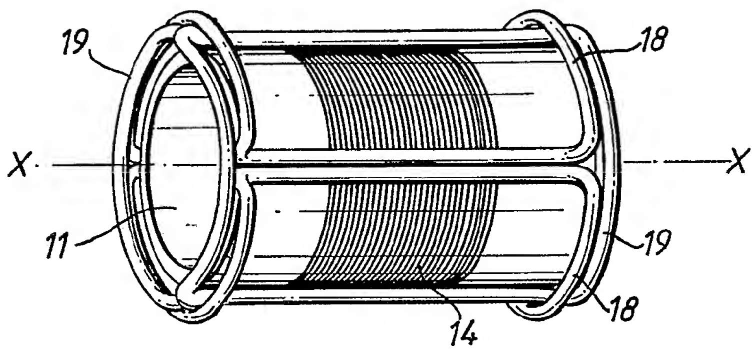

FIG. 5.

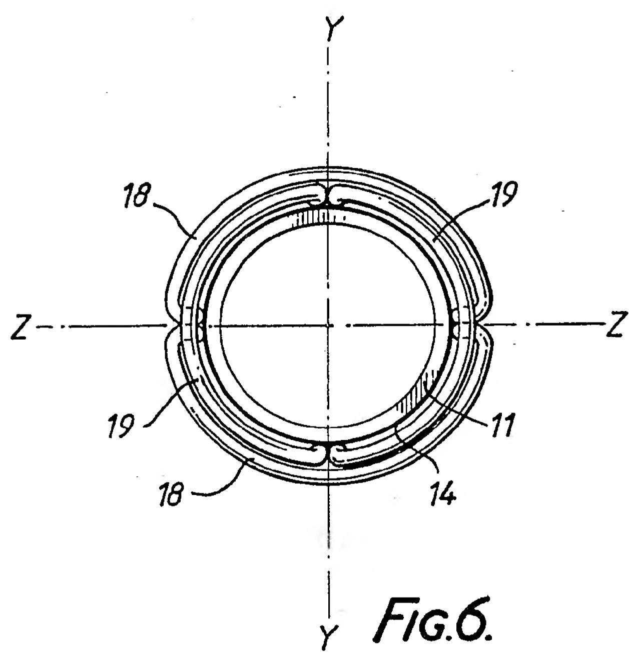

FIG. 6.

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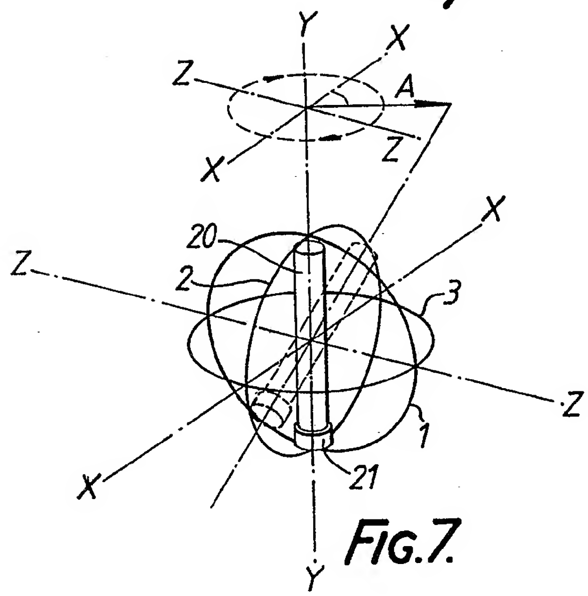

FIG.7.

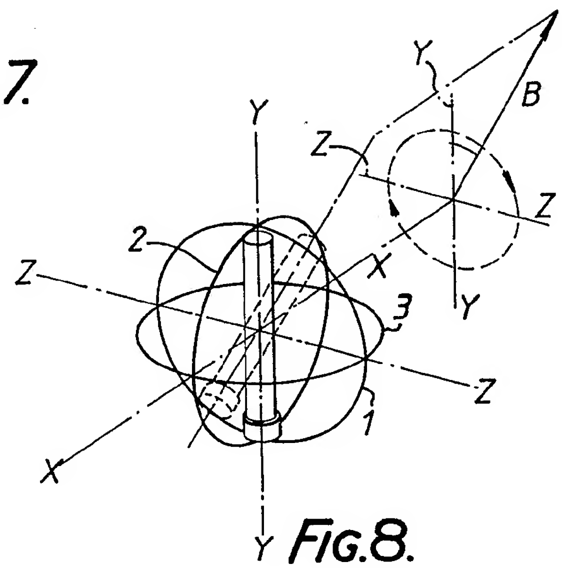

FIG.8.

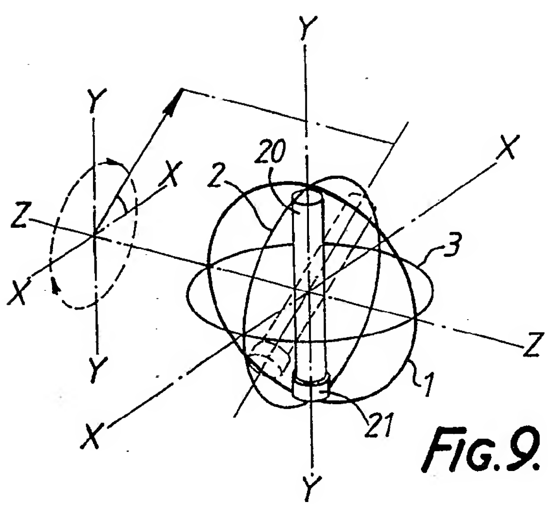

FIG.9.

SPECIFICATION

Improvements relating to positional information systems

This invention is concerned with means for transmitting information about the relative positions in space of a transmitter and receiver, or of transmitter tilt relative to a gravity determined vertical. It has particular application to systems for measurement and/or guidance of the position and attitude of soil piercing or boring tools, but is by no means limited to such applications.

According to one aspect of the present invention there is provided a positional information system comprising a transmitter for producing a varying electromagnetic field having a set of coils with three mutually orthogonal intersecting axes and means for energising the coils in pairs with a.c. in a phase relationship that generates a resultant field rotative about the axis of the other coil, a receiver coil and means for determining from the receiver coil the phase relationship of the induced signal to the transmitted signals, thereby providing an indication of the positional relationship between the receiver coil and the transmitter.

Preferably, there will be three receiver coils in a mutually orthogonal relationship similar to the transmitter, each contributing positional information derived from phase relationships.

The transmitter coils may be energised in pairs in sequence, using the same frequency, or each pair may use a different frequency, allowing simultaneous transmission.

The coils will preferably be annular and may be wound on formers around a spherical ferromagnetic core. However, in certain circumstances this configuration is not feasible, and may have to be varied. An example will be described, particularly applicable to underground boring devices.

According to another aspect of the present invention there is provided a positional information system comprising a transmitter for producing a varying electromagnetic field having a set of coils with three mutually orthogonal intersecting axes and means for energising the coils in pairs with a.c.in phase relationship that generates a field rotative about the axis of the other coil, a magnetically susceptible body with a defined magnetic axis suspended in proximity to the transmitter, and means for determining from any coil the phase relationship of the signal induced therein to that energising either of the other two coils and thereby provide an indication of the orientation of said body.

Preferably, the coils will be annular and wound on formers in the shape of a spherical cage. The body is then suspended symmetrically at the centre point and the cage will be arranged so that one coil axis is normally vertical and co-incident with the axis of the body. The latter may simply be a ferromagnetic rod, with a bias weight to hold it upright. Signals from the coils in receiver mode can be processed to indicate the tilt of the rod and its direction of inclination.

For a better understanding of the invention, some embodiments will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 shows side views of a coil assembly for producing rotating electromagnetic fields,

Figure 2 is a diagrammatic perspective view of the coil assembly, with a sensor coil in various positions.

Figure 3 is a perspective view of a receiver coil assembly suitable for mounting on an underground boring tool or "mole",

Figure 4 is a perspective view of a mole equipped with a receiver coil assembly of Figure 3 and a remote transmitter coil assembly arranged to excite the coils on the mole for orientation purposes,

Figure 5 is a perspective view of an alternative receiver coil assembly,

Figure 6 is an end view of the assembly of Figure 5, and

Figures 7,8 and 9 are diagrammatic perspective views of a tilt sensor employing the three coil assembly of Figure 1.

The basic equipment is a set of three similar coils 1,2 and 3 with mutually orthogonal axes intersecting at a common centre, these coils being excited in pairs with 2-phase alternating current to establish rotating electromagnetic fields about each of the three axes, either separately and in sequence at a common frequency, or simultaneously at different frequencies. The production of a rotating field by 2-phase windings is commonplace in a.c. motor technology and will not be described in detail. The coils 1,2 and 3 are wound on formers fixed at right-angles to each other e.g. by adhesive, and if desired the fields they produce may be strengthened by incorporating a ferromagnetic core 4. This must be spherical and homogeneous if it is not to introduce variations in field intensity through variations in permeability in different directions, and may in practice be constructed of high permeability low conductivity material such as powdered iron or ferrite. The core would be omitted for applications in which the internal field is sensed, as described later.

Referring now to Figure 2 it will be apppar-ent that exciting coils 1 and 2 only with 2-phase a.c. will produce a resultant field A rotating about the vertical axis Y of coil 3. Exciting coils 2 and 3 only will produce a resultant field B rotating about the horizontal axis X of coil 1, while exciting coils 3 and 1 only will produce a resultant flux C rotating about the horizontal axis Z of coil 2. In all cases the direction of rotation depends on the phase rotation.

For determination of the relative positions of this three-coil transmitter and a receiver, the external field is sensed. Figure 2 illustrates the effect on an external search coil of exciting coils 1 and 2 only to produce the resultant field A rotating at supply frequency about the Y axis, and therefore of maximum amplitude in the horizontal plane X-Z through the coil centre.

At position 5 the search coil is initially aligned with the X axis. It is swept each cycle by resultant field A, with its signal peak amplitude corresponding in time to peak excitation of the coil 1, and a null corresponding to peak excitation of the coil 2. The signal will therefore be nominally in phase with the excitation of coil 1. It will be apparent that if the search coil remains in the same plane pointing towards the coil centre but is swung around to position 6, for example, its signal will still have the same amplitude, but will no longer be in phase with coil 1; the change of phase angle will correspond with the change in mechanical angle, because the field structure is equivalent to that of a 2-pole induction motor, in which electrical and mechanical degrees have the same values. But if the same search coil remains at position 5, but is rotated about its centre in the horizontal plane, as suggested by the dotted circle, the signal will exhibit a similar phase change to that caused by swinging it around the coil centre, because its peak will always occur when the radial direction of the resultant flux A is parallel to the search coil. So if it were possible to establish independently the radial position of the search coil about the transmitter centre, the signal phase would establish the rotational attitude of the search coil axis to that radius. This shows one aspect of the system properties.

Consider again the search coil at position 6, initially radially aligned with the transmitter centre in the horizontal plane, but then rotated abouts its centre in the vertical plane, as indicated by the dotted line. It will be apparent that the signal will remain constant in phase but decrease in amplitude until the search coil is vertical, when a null point is reached. Rotation beyond this will produce a signal of opposite phase sense increasing in amplitude until the search coil is again horizontal 180° from its starting point. So rotation in this plane produces a distinctive change in signal amplitude, with phase reversal at the 90° and 270° positions.

Having moved the search coil into the vertical position relative to the horizontal plane, when it will experience a null signal, consider the effect of rotating it about the radial axis as indicated at position 7. Its signal amplitude will increase from null at the vertical position to reach a maximum when horizontal, with a further null and phase reversal at 180°.

In each case considered, there is a mathematical relationship between the phase and amplitude of the signal at the search coil and the latter's position and attitude relative to the transmitter. Trigonometrical formulae can be established covering the case in which the measurements are restricted to movements in the horizontal plane about the transmitter centre.

If the plane in which the search coil is moved is now lifted e.g. to point 8, it will be clear that the signal amplitude will reduce because the new plane is no longer coincident with the X-Z plane in which the peak occurs. Otherwise its response will vary in a similar manner to a coil in that the X-Z plane, and the effects of shifting the plane of search are subject to mathematical formulae which can be established.

Consider now the effect on the search coil of excitation of the coils 2 and 3 to produce resultant field B rotating about the X axis.

With the search coil at position 5 and aligned on that axis, there will be no signal from resultant field B. If rotated in the horizontal plane while remaining centred on the X axis the search coil will show a signal of nominally constant phase but increasing amplitude, reaching a peak at the 90-270° position transverse to the X axis, with a phase reversal at 180°.

If, however, the search coil is rotated in the vertical plane about the X axis as shown by position 9, the signal phase change will correspond with the rotation of the field about the X axis, with its amplitude varying with displacement from the axis. Thus at position 7 it will be reduced, and when it is displaced as far as the Z axis, there will be no response.

For rotation of the search coil in the X-Y plane as shown by position 10, there will be a change of amplitude from a null when horizontal to a peak when vertical, with phase reversal at the 180° horizontal position. As it is displaced in the X-Z plane, e.g. to position 6, the signal will be quite dissimilar to that resulting from excitation of coils 1 and 2, but mathematically predictable.

It will be understood that excitation of coils 3 and 1 to produce resultant field C rotating about the Z axis will also produce mathematically definable signals at the various possible positions of the search coil. Because these differ with the axis of field rotation, it is possible to obtain three sets of information about the relative positions and attitudes of a three-coil transmitter and a single search coil.

If a receiver is used which effectively incorporates three aerials on mutually orthogonal axes, the amount of positional information which can be derived from the rotating fields is greatly increased. Such an aerial may be constructed in similar fashion to the transmitter. Where the situation does not allow for a solid core, as for example behind a soil piercing tool or mole, for which fluid power and control cable access is required, a toroidal

core design may be used, similar to that described in our previous application No. GB-A-2,175,096, but wound with coils serving three axes. One example of this is illustrated schematically in Figure 3.

The core is typically a spirally wound toroid of suitable steel 11. Taking its longitudinal axis as X, its vertical axis as Y and its horizontal axis as Z, it is possible to use all this core material in common to provide enhanced coupling of a.c. electromagnetic fields to three windings on these three axes. A pair of toroidally wound coils 12 disposed diametrically opposite one another across the horizontal diameter and connected in series will respond to a.c. field components on the vertical axis Y, and a similar pair 13 on the vertical diameter will sense a.c. field components on the horizontal axis Z. A coil 14 wound co-axially around the outside of the toroid will detect a.c. field components along the axis X. The annular construction allows for central passage of pipes and cables when a 3-axis aerial of this form is attached to the back of a soil piercing tool.

Figure 4 illustrates a 3-axis transmitter 15 as shown in Figures 1 and 2 and an aerial 16 as shown in Figure 3 applied to position and attitude sensing of a soil piercing mole 17 below ground. The transmitter and receiver electrical power supplies and electronic systems for data retrieval and display are not shown, as these utilise conventional techniques familiar to electronic engineers. The transmitter 15 is positioned below ground in an access pit in line with the projected hole to be bored, but accurately sited for verticality and direction.

If the mole 17 is steerable by remote control, it is vital that its roll attitude (rotation about longitudinal axis X) is established so that the steering elements operate in the correct direction. It will be apparent that, if the transmitter 15 has 2-phase a.c. applied to coils 2 and 3 to give resultant field B rotating about the X axis, the signal detected by the Y axis coils 12 of the receiver will have a phase relationship relative to the transmitter frequency which is directly related to roll angle. This can be related to the Figure 2 search coil at position 9. The same would also be true for the signal from the receiver Z axis coils 13, but shifted 90° in phase. There should be a null signal from the receiver longitudinal X axis coil 14 as long as the mole and its receiver remain on that axis.

If the transmitter coils 3 and 1 are energised to produce resultant field C rotating about the horizontal Z axis of the transmitter, the receiver X axis coil signal will have a phase relationship with the transmitter frequency which will change with pitch of the mole and receiver.

The system is therefore capable of detecting roll, pitch and yaw from phase angle measurements, but it will be obvious that, as pitch and yaw angle increase towards 90°, the phase change effects will pass from one receiver axis to another. By comparing the signals on each axis, which must still follow mathematically predictable relationships, it is possible to establish by use of all three axes of transmission not only roll, pitch and yaw, but also the coordinate position of the receiver relative to that established when the transmitter was sited, taking into account any off-axis displacement of the transmitter. With a steerable mole, the system may be used to obtain positional information to enable it to be steered along a predetermined course.

The three axes of the transmitter may be energised sequentially at the same frequency or simultaneously at different frequencies, filtering of the receiver signals being then used to discriminate between the three axes. Because three sets of information are available for each receiver axis, the system provides for continuous cross-checking of the positional data through suitable computer hardware.

A possibly more practical toroidal transmitter is illustrated in Figures 5 and 6, where the core 11 and coil 14 are as in Figure 3. However, instead of winding coils 12 and 13 in laborious fashion by taking turns through the core, they are replaced by wholly external coils 18 and 19. These are constructed as rectangular, former wound coils held to the core by straps (not shown) or other means and the series connected pairs are arranged in mutually orthogonal relationship. They are similar to induction motor windings for a two pole stator, except that the 'stator' in this case is inside out and slotless. Apart from simpler construction, inter-winding coupling should be minimised.

The foregoing description has covered typical techniques for sensing the external field of the transmitter, and applying the information to relative position sensing of transmitter and receiver. Another application of the 3-axis transmitter is to tilt sensing, when its internal field is sensed, and Figures 7,8 and 9 illustrate this.

The same transmitter coil configuration is used, but the solid ferromagnetic core is omitted. Instead, a ferromagnetic rod 20, preferably of ferrite, is suspended about the coil centre by a gimbal mounting, for example, so that it is free to pivot in any direction.

The rod 20 is provided with a weight 21 so that it maintains itself vertical by gravitational force. It is drawn in full in its datum or reference position aligned with the Y axis, and in broken lines displaced from this reference position by an arbitrary amount. Although for convenience the coils are drawn remaining in their original attitudes, it will be appreciated that the displaced position of the rod 20 represents the situation produced when the coil Y axis tilts from vertical, but the rod re-

mains vertical.

In Figure 7, the coils 1 and 2 are energised with 2-phase a.c. to produce resultant field A rotating about the Y axis. If the emf induced in coil 3 is sensed, it will be found to have a null signal with the rod vertical, because there is no component of rotating field A along the rod axis. However, at this point there is maximum coupling between the rod and the coil 3, which will therefore be most sensitive to any field linking the rod, as soon as tilt occurs. When it does, as exemplified by the tilted rod, the signal induced will be at a peak when the resultant field A is in the direction of tilt in the X-Z plane, which is represented by angle *r*. The phase of the coil 3 signal relative to the supply frequency at coil 1 will therefore give the direction of tilt in this plane.

Figure 8 shows the same situation with coils 2 and 3 energised to produce resultant field B rotating about the X axis. This time the signal in coil 1 is sensed, which will have a phase relationship with the supply frequency defining the angle *s* to the Y axis of the rod in the Y-Z plane.

Similarly, Figure 9 shows the effect of energising coils 3 and 1 to produce resultant field C rotating about the Z axis, and sensing the coil 2 signal. Again the phase relative to the supply will define the angle *t* projected by the rod onto the X-Y plane.

So by sensing each plane in turn, the tilt of the transmitter relative to a gravitationally orientated body can be established in two planes related to the transmitter itself; any rotation of the transmitter in the horizontal plane would need to be established separately if of importance for a particular application.

While described as for a tilt-sensing application, it will be obvious that any gravity-related measurement will be effected by acceleration of the transmitter if in motion, so that the device may also be used as a directional accelerometer. Also, while the tilt-sensing embodiment has been described using a gimbal-mounted rod, other techniques may be used to avoid the use of mechanical bearings, e.g. by floating a layer of ferromagnetic fluid on another fluid of higher density in a spherical container, to provide a disc of ferromagnetic material in place of the rod, which will also produce signals varying in time phase to indicate tilt in a similar manner.

CLAIMS

1. A positional information system comprising a transmitter for producing a varying electromagnetic field having a set of coils with three mutually orthogonal intersecting axes and means for energising the coils in pairs with a.c. in a phase relationship that generates a resultant field rotative about the axis of the other coil, a receiver coil and means for determining from the receiver coil the phase relationship of the induced signal to the transmitted signals, thereby providing an indication of the positional relationship between the receiver coil and the transmitter.

2. A system as claimed in Claim 1, wherein there are three receiver coils in a mutually orthogonal relationship similar to the transmitter, each contributing positional information derived from phase relationships.

3. A system as claimed in Claim 1 or 2, wherein the transmitter coils are energised in pairs in sequence, using the same frequency.

4. A system as claimed in Claim 1 or 2, wherein the transmitter coils are simultaneously energised in pairs with different frequencies.

5. A system as claimed in any preceding claim, wherein the coils are annular and wound on formers around a spherical ferromagnetic core.

6. A positional information system comprising a transmitter for producing a varying electromagnetic field having a set of coils with three mutually orthogonal intersecting axes and means for energising the coils in pairs with a.c. in a phase relationship that generates a field rotative about the axis of the other coil, a magnetically susceptible body with a defined magnetic axis suspended in proximity to the transmitter, and means for determining from any coil the phase relationship of the signal induced therein to that energising either of the other two coils and thereby provide an indication of the orientation of said body.

7. A system as claimed in Claim 6, wherein the transmitter coils are energised in pairs in sequence, using the same frequency.

8. A system as claimed in Claim 6, wherein the transmitter coils are simultaneously energised in pairs with different frequencies.

9. A system as claimed in Claim 6,7 or 8, wherein the coils are annular and wound on formers in the shape of a spherical cage.

10. A system as claimed in Claim 9, wherein the body is suspended symmetrically at the centre point of the cage.

11. A system as claimed in Claim 10, wherein the cage is arranged so that one coil axis is normally upright and coincident with the axis of the body.

12. A system as claimed in any one of Claims 6 toll, wherein the body is a ferromagnetic rod with biasing means to hold it upright.

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